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Investigation of unsteady flow-induced impeller oscillations of a single-blade pump under off-design conditions

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ABSTRACT

The periodically unsteady flow-induced impeller oscillations for a single-blade pump are investigated both numerically and experimentally under off-design conditions. A partitioned strategy with load transfer method is selected for achieving successful fluid–structure interaction (FSI) simulations with strong two-way coupling. Three-dimensional, unsteady Reynolds-averaged Navier–Stokes equations are solved with a shear stress transport turbulence model for the fluid side, while a transient structure dynamic analysis with the finite element method is employed for the structure side. Radial deflections of the pump impeller are successfully measured using proximity sensors to validate the FSI results. The comparison of the deflection results focuses on both phase and amplitude aspects under different operational conditions. The FSI calculation results are confirmed by the experiment, but deviations are still observed for about half of an impeller rotation. Therefore, a rigorous analysis of the comparison between the angles of the obtained x and y components is carried out to understand the cause of the deviation. Meanwhile, the transient pressure measured at the casing by both computational fluid dynamics and experimental methods is qualitatively analyzed. Furthermore, hydrodynamic forces are also analyzed considering a strong FSI effect in both the rotating and stationary coordinate frame under off-design conditions to understand the behavior of the transient excitation forces, which directly lead to the rotor deflection.

1. Introduction

A centrifugal pump is one of the most important energy conversion devices and is widely used in almost all industrial and agricultural applications. Single-blade pumps with a special impeller design are used for transporting water containing large amounts of solids and fibers, and are called no-clogging sewage water pumps. This type of impeller geometry, however, results in a strong asymmetrical unsteady flow and consistent periodically unsteady excitation forces under design condition and an even stronger asymmetrical unsteady flow under off-design conditions, due to a hydrodynamic unbalance (Agostinelli et al., 1960; Aoki, 1984; Okamura, 1980). This leads to impeller oscillations and alternating stresses, designated as a flow-induced vibration problem (Guelich, 2007). Not only the impeller itself, but also other pump components, such as the casing and bearings, may be damaged by these oscillations and the corresponding transmitted vibrations.

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Nomenclature

a	load component
b_2	blade height at impeller outlet
d_s	pipe diameter at pump suction
F_{ref}	reference force
F_x, F_y	force components along x and y axes
F_ξ, F_ψ	force components along ξ and ψ axes
H	delivery head
H_s	supply head
H_{des}	delivery head under design condition
n	rotation speed
n_{des}	nominal rotation speed
p_c	pressure at casing
Q	flow rate
Q_{des}	flow rate under design condition
r_2	radius at impeller outlet
S	rotor deflection
S_x, S_y	rotor deflection components along x and y axes
$S_{x,0}$, $S_{y,0}$	initial values of rotor deflection components along x and y axes
$S_{x,test}$, $S_{y,test}$	test oscillation values of rotor deflection components along x and y axes
$S_{x,wet}$, $S_{y,wet}$	values of rotor deflection components along x and y axes under "wet" condition
$S_{x,dry}$, $S_{y,dry}$	values of rotor deflection components along x and y axes under "dry" condition
u_2	circumference velocity at impeller outlet
x, y	coordinates in stationary frame

Greek letters

Δ	difference
ξ, ψ	coordinates in rotation frame
ρ	density
ϕ	convergence criterion
φ	angle of rotation

To solve this problem, the analysis of the unsteady flow field and structural dynamic response of a pump impeller should consider the fluid–structure interaction (FSI), which in this case, refers to the interaction between the complex inner flow and structures of centrifugal pumps. In FSI, the hydraulic excitation changes the kinetic characteristics of the structures and leads to the deformation of these structures, which can affect the distribution of the pump inner flow field. Although research on the application of computational fluid dynamics (CFD) and computational structural dynamics (CSD) is yet in its nascent stages, the maturity of these methods is sufficient to enable the numerical simulation of FSI. To solve complicated FSI problems, two strategies can be used depending on the physical nature of the interaction (Felippa and Park, 1980; Piperno and Farhat, 2001): the monolithic approach and partitioned approach.

The monolithic method requires a straightforward solution for all unknowns of the overall coupled system and solves the resulting system of equations with a complete tangent stiffness matrix. In this way, all interaction effects between the dependent equations are addressed in one solver. This approach is ideal when the physical interactions are strongly non-linear; however, it is currently difficult to implement because of some severe drawbacks, such as the complex modeling required for both fluid and structure fields and the large computational resources required.

In the partitioned method, the equations governing the flow and the displacement of the structure are solved separately in different solvers without any limitation. This enables us to exploit the advantages of mature solvers for both CFD and CSD, which have been developed in recent years for engineering applications, precluding the need for developing a specialized solver for an FSI problem. The interaction effects between both physical fields are represented by an exchange of loads (total force and mesh displacement) at the common interface. For the solid component, the natural view is the material (Lagrangian) description, and for the fluid, it is the spatial (Eulerian) description. Combining these views requires a mixed description for the partitioned method, and for this purpose, the arbitrary Lagrangian–Eulerian description (Belytschko and Kennedy, 1978; Belytschko et al., 1980; Hughes et al., 1981) is usually selected.

Although FSI problems have received significant attention, only a small number of research studies have been conducted to experimentally validate complex FSI problems in engineering fields because in some cases, the deformations are negligible or cannot be easily measured for moving or rotating structures due to the limitations of the measurement methods and equipment. In the research area of fluid machinery, some numerical research was conducted with a coupled method, but only a few studies considered the vibration problems of pump machinery in which water was the operational medium, such as the works by Benra (2006), Benra et al. (2006), Benra and Dohmen (2007), Campbell and Paterson (2011), Gnesin and Rzadkowski (2002), Kato et al. (2005), Langthjem and Olhoff (2004), and Muench et al. (2010). These numerical and experimental studies offer insight on flow-induced vibration and noise phenomenon in fluid machinery; however, only a few considered the integrated interaction between the fluid and solid with a strongly coupled analysis. Furthermore, for off-design operational conditions, no sufficient numerical and experimental results were compared and analyzed in detail.

The present research is an improvement over former works, with more thorough analyses and the following new aspects:

(1) A full two-way coupling calculation, which includes stagger iterations between the two solvers for each time step, was conducted to obtain strongly coupled results for an impeller deflection calculation. The stagger iterations were not